Decaying Asymmetric Dark Matter Relaxes the AMS-Fermi Tension

Lei Feng[1] and Zhaofeng Kang[2,*]

[1] *Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210008, China*

[2] *Center for High-Energy Physics, Peking University, Beijing, 100871, P. R. China*

(Dated: April 30, 2013)

Abstract

The first result of AMS-02 confirms the positron fraction excess observed by PAMELA, but in the dark matter (DM) interpretation, its softer spectrum brings a tension between AMS-02 and Fermi-LAT, which reported an excess of the electron plus positron flux. In this work we point out that the asymmetric cosmic ray from asymmetric dark matter (ADM) decay relaxes the tension, and find that at the two-body decay level a bosonic ADM around 2.4 TeV and decaying to $\mu^-\tau^+$ can significantly improve the fits. Based on the $R-$parity-violating supersymmetry with operators LLE^c, we propose a minimal model to realize that ADM scenario: Introducing a pair of singlets $(X, \bar{X})$ and coupling them to the visible sector via LH_uX, we then obtain a leptonic decaying ADM with TeV-scale mass.

PACS numbers: 12.60.Jv, 14.70.Pw, 95.35.+d

*Electronic address: zhaofengkang@gmail.com

I. INTRODUCTION AND MOTIVATIONS

Dark matter (DM) is commonly accepted as a major component of our Universe in the present era, and its fraction in the total energy budget is precisely determined to be 26% [1]. Nevertheless, the most confirmative evidences for its existence all come from its gravitational effects, rendering its particle properties barely known. In the galaxy, DM may annihilate or decay into cosmic ray (CR) components, such as $e^{\pm}$ and $p/\bar{p}$, which induce the CR excesses or CR anomalies. The observation of such anomalies by means of indirect DM detections can be regarded as a smoking-gun for the DM particle evidence.

Recently, such smoking-guns have been triggered. In the year 2008, PAMELA reported that the positron fraction of the CR shows a sharp rising excess over the background, within a region from 10 GeV to 100 GeV [2]. This excess is extended to higher energy by PAEMLA and FERMI [3], in spite of a larger error bar. It is of great interest to attribute the excess to extra e^+/e^- from DM decay or annihilation. Even more excitingly, the DM interpretation is well consistent with another important excess from the 2009 Fermi-LAT, which precisely measured the total flux of electrons and positrons and observed a flat excess up to the TeV region [4] [40]. On the other hand, both the PAMELA anti-proton [5] and Fermi-LAT diffuse gamma ray [6] data are well fitted by the pure backgrounds, which then stringently restrict possible dark matter explanations. In practice, the inverse Campton scattering (ICS) process of the injected e^+/e^- always produces an associated diffuse gamma ray spectrum. Note that the injected e^+/e^- flux is proportion to $\rho_{\rm DM}(r)^2$ and $\rho_{\rm DM}(r)$ in the annihilating and decaying DM scenarios, respectively. Thereby, to evade the exclusion from Fermi-LAT, the decaying DM scenario is strongly favored [7]. In supersymmetric standard models (SSMs), the required extremely long lifetime $\sim 10^{26}$s and leptonic final states, can be realized by introducing proper $R-$parity violating operators [9], or dimension-six operators suppressed by the GUT-scale [10, 11] and further aided by some flavor symmetry [11].

Very recently, the long-expected AMS-02 experiment released the first result of positron fraction measurement [12]. It measures the fraction over a much wider energy region, from 0.5 to 350 GeV, with an unprecedented high precision. It confirms the excess, and largely speaking, is consistent with the PAMELA result. Nevertheless, at the same time it brings a clear tension with the Fermi-LAT total flux measurement [13–16, 18]. The tension is ascribed to the fact that the first AMS-02 result exhibits a softer behavior than the PAMELA result at higher energy (As Ref. [12] emphasized, the slope of the spectrum decreases one magnitude of order from 10 to 250 GeV). Consequently, as we fit Fermi-LAT using a relatively heavy DM, the resulted positron fraction at higher energy will be too hard to fit AMS-02 (The same problem may also be encountered in the pulsar explanation [17, 18]). To reconcile AMS-02 and Fermi-LAT, we may need to consider nonconventional scenarios of CR, which can give a

relatively harder e^- spectrum than the e^+ spectrum. For instance, an astrophysical solution like hardening the primary e^- spectrum at higher energy [13, 18, 19].

Viewing from the particle physics, hardening the e^- spectrum can be naturally achieved by updating the decaying DM to the asymmetric decaying DM. In this framework, when the asymmetric DM decay produces asymmetric final states, say $\mu^-\tau^+$ but with vanishing conjugate states $\mu^+\tau^-$, then the asymmetric cosmic ray with harder e^- spectrum (than the e^+ spectrum) is generated. Actually, such a scenario has already been studied even at the time when only the PAMELA data is available [20, 21]. AMS-02 result may favor it [41].

This paper is organized as follows. In Section II, a model independent fit of the AMS-02 and Fermi-LAT data is employed, assuming that the (scalar) asymmetric DM asymmetrically (two-body) decays to a pair of charged leptons. In Section III, we propose a minimal supersymmetric decaying asymmetric DM model. The Section IV is the discussion and conclusion. Some necessary and complementary details are given in Appendices A.

II. ASYMMETRIC COSMIC RAY RELAXES THE AMS-FERMI TENSION

As has been pointed out in the introduction, to well fit the high precision experiments AMS-02 and Fermi-LAT data simultaneously, the main difficulty lies in fitting the higher energy of AMS-02 (after fitting Fermi-LAT), which gives a relatively soft positron fraction spectrum. A way out of this difficulty is through going beyond the symmetric CR and assuming the injected CR is asymmetric, namely the fraction

$$r^+(E) \equiv \frac{\Phi^+(E)}{\Phi^+(E) + \Phi^-(E)} \neq 0.5, \tag{1}$$

Generically, $r^+(E)$ has a energy dependence. Note that such a solution is thanks to the fact that Fermi-LAT is bind to the sign of charges. In this work, we consider the following three asymmetric modes from a scalar DM decay (See also [20]):

$$X \to e^-\mu^+, \quad e^-\tau^+, \quad \mu^-\tau^+. \tag{2}$$

In Ref. [21], the fermionic DM decaying to lepton plus a charged Higgs boson or W boson is considered, but that may produce too much anti-protons and thus is disfavored (In fact, the fits are even worse than the ordinary case).

We now employ data fitting and find out the best mode. The propagation of CR in the Milk Way is described by a Boltzmann equation, and in principle we can obtain the fluxes of CR components by solving this equation using the corresponding boundary conditions. However, it is difficult to analytically solve the propagation equation, due to the complicated distributions of sources, interstellar matter, radiation field and magnetic field. So, here we

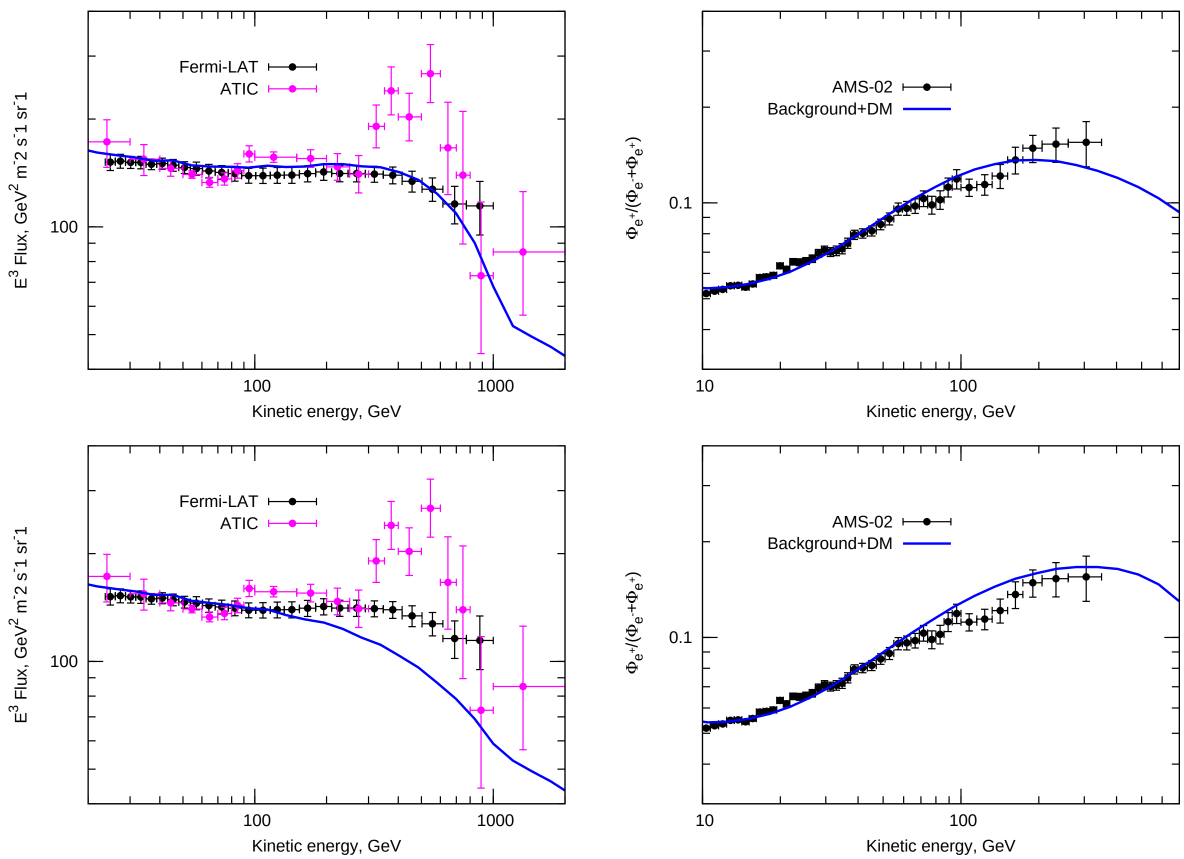

FIG. 1: Top-panels: Fits for the AMS-02 positron fraction spectrum (right) and the Fermi-LAT $e^- + e^+$ flux spectrum (left), using an asymmetric cosmic ray originating in an asymmetric dark matter decaying to $\mu^- + \tau^+$. The best fit is achieved for the dark matter with mass 2.4 TeV and lifetime 2×10^{26} s. Bottom-panels: A comparison to the best fit using the symmetric cosmic ray from DM decaying to $\tau^+\tau^-$.

use the GALPROP [22] package to numerically calculate the propagation of particles in the CR, and we modify the code to include the contribution from DM decay. During our fitting, we take the following parameters for the CR propagation : The diffusion coefficient $D_0 = 5.3 \times 10^{28}$ cm^2 s^{-1}, the diffusion index $\delta = 0.33$, the Alfven velocity $V_\mathrm{A} = 33.5$ km s^{-1} and the Halo height $z_\mathrm{h} = 4$ kpc. Furthermore, the injection indexes of nucleon below and above the break rigidity $\rho_\mathrm{br} = 11.5$ GV are 1.88 and 2.39, respectively. Finally, as for the DM distribution function, we use the Einasto density profile [23]:

$$\rho(r) = \rho_s \exp\left(-\frac{2}{\alpha_s}\left[\left(\frac{r}{r_s}\right)^{\alpha_s} - 1\right]\right), \tag{3}$$

where $\alpha_s = 0.17$, $\rho_s \approx 0.14$ GeV cm^{-3} and $r_s \approx 15.7$ kpc.

The result is shown in Fig. 1. Among the modes listed in Eq. (2), we find that the best mode is $X \to \mu^-\tau^+$, with a $\chi^2 = 90.4$. The corresponding ADM mass and lifetime are 2.4

TeV and 2×10^{26} s, respectively. The fits for the AMS-02 and Fermi-LAT data are shown in the top panels of Fig. 1. As a comparison, we also display the fits in the symmetric decaying DM case, see the bottom panels of Fig. 1. The best fit is achieved for a similar DM but decaying to $\tau^+\tau^-$, and the chi square is much worse, $\chi^2 = 205.0$.

III. ASYMMETRIC COSMIC RAY FROM ASYMMETRIC DM DECAY

In particle physics, it is natural to expect that the asymmetric CR originates from asymmetric dark matter (ADM) decay [20, 21]. However, for the sake of naturally solving the cosmic coincidence puzzle, namely $\Omega_b h^2 : \Omega_{\rm DM} h^2 \simeq 6 : 1$, the ADM mass is expected to be around 10 GeV [21] rather than at the TeV scale inspired by solving the AMS-Fermi tension. Additionally, it is difficult to embed ADM into the simple supersymmetric standard models (SSMs) such as the minimal-SSM (MSSM) and its singlet (e.g., the NMSSM) or right-handed neutrinos extensions, owing to the robust neutralino mediated charge wash-out effect [25]. In this section we will first construct a simple and natural model to address these problems and then discuss the phenomenological aspects of the model.

A. TeV-scale decaying ADM

Within the conventional ADM framework [26], dark matter carries a generalized lepton or baryon number through proper couplings to the standard model (SM) matters. Effectively, this can be described by the operators such as $\mathcal{O}_T = \mathcal{O}_{\rm DM}\mathcal{O}_{\rm SM}(\ell, q)$ which, above some temperature T_D, establish the chemical equilibrium between the dark sector and visible sector, and leads to [27]

$$\sum_i \mu_{\phi_i} = 0, \tag{4}$$

with μ_{ϕ_i} the chemical potential [27] of the particles appearing in the previous operators. In other words, they transfer the visible sector matter asymmetry (Assumed to be generated via some visible sector dynamics) to the hidden sector, which is symmetric if $\mathcal{O}_T$ is turned off. Eq. (4) indicates that the chemical potentials of two sectors should be at the same order.

Further, for the particles in the thermal bath with temperature T, their asymmetries can be expressed with the corresponding chemical potentials [28]

$$\begin{aligned} n_+ - n_- &= g\frac{T^3}{\pi^2}\frac{\mu}{T}\int_0^\infty dx \frac{x^2 \exp[-\sqrt{x^2+(m/T)^2}]}{\left(\theta + \exp[-\sqrt{x^2+(m/T)^2}]\right)^2} \\ &\equiv \begin{cases} f_b(m/T) \times g_b \frac{T^3}{6}\left(\frac{\mu}{T}\right), & \text{(for bosons)} \\ f_f(m/T) \times g_f \frac{T^3}{6}\left(\frac{\mu}{T}\right), & \text{(for fermions)} \end{cases} \end{aligned} \tag{5}$$

where θ takes 1 and -1 for a boson and fermion respectively. g denotes the internal degrees of freedom. The Boltzmann suppression factors $f_{b,f}(m/T)$ indicate the threshold effects for heavy particles. For particles in the ultra-relativistic limit, i.e., $m \ll T$, $f_{b,f}$ tend to 2 and 1, respectively. Oppositely, the asymmetry of the decoupling particle can be greatly suppressed. Provided that only the asymmetric component leaves, we then have

$$\frac{\Omega_b h^2}{\Omega_X h^2} = \frac{m_p}{m_X} \frac{\sum_q \mu_q}{g_X f_X \mu_X}, \tag{6}$$

with m_X the DM mass. Thereby, when the transfer ceases at a temperature far above m_X, the conventional scenario [26], it is found that $m_X \sim 10$ GeV is predicted to solve the cosmic coincidence puzzle. By contrast, when the chemical equilibrium decoupling happens during the period of DM entering non-relativistic, then the puzzle has to be resolved by a heavy DM [29, 30]. In spite of a sensitive dependence on the ratio m/T, ADM in this scenario still has a dynamical origin for its similar relic density to the baryonic matter's (Beyond the chemical equilibrium mechanism to generate DM asymmetry, there are other ways to get a heavy ADM [31].).

To realize a leptonic decaying ADM, it is tempting to consider that $\mathcal{O}_T$ does not involve quark matters and moreover provides a path for DM decaying into leptons. It can be achieved by forcing X to develop a vacuum expectation value (VEV) v_X, which breaks the symmetry for DM stability. However, bare in mind that here the decaying DM is extremely long lived, so either a very small v_X or exceedingly suppression from the operator coefficients is indispensable. The former, in principle is possible given some complicated dynamics, while the latter is inconsistent with the TeV scale ADM set up because it requires the operators to decouple below m_X. Then we are led to the scenario where an extra source slightly violates the symmetry protecting DM stability. A good case in point is the $R-$parity-violating SUSY, where the tiny $R-$parity violations are spectator to the usual dark matter dynamics and only account for DM late decay. So, in the following subsection we will introduce a leptonic decaying ADM based on the $R-$parity-violating SUSY.

B. A minimal supersymmetric model

Now we embed a heavy decaying ADM in SUSY. Due to the neutralino mediated wash-out effect [25], ADM is difficult to be accommodated in the popular supersymmetric models. Within the chemical equilibrium framework, Ref. [29, 30, 32] considered high dimension operators such as $\mathcal{O}_T = X^2 LLE^c$ with a new and relatively low cut-off scale. Here we construct a more economic model, even without incurring any new scales in the superpotential. On that purpose, a minimal model may take a form of (Actually, it resembles the supersymmetric

inverse seesaw model proposed in Ref. [33], where a light ADM is studied):

$$\begin{aligned}W =&\lambda_{ijk}L_iL_jE_k^c + \left(y_{iX}L_iH_uX + \lambda_X SX\bar{X}\right)\\&+\left(\lambda SH_uH_d + \frac{\kappa}{3}S^3\right) + W_{\rm MSSM}.\end{aligned}\tag{7}$$

The corresponding soft terms are implied. L_i and L_j are asymmetric, and thus $\lambda_{ijk} = -\lambda_{jik}$. We order $i < j$ hereafter. The superpotential is divided into three sectors: the $R-$parity-violating sector which accounts for the ADM leptonic decay, the dark sector, of which a single family of lepton will be considered for simplicity (hereafter $y_{iX} \to y_X$), and the ordinary NMSSM sector, i.e., terms in the second line, which dynamically generates the low energy scales via the singlet VEV $\langle S\rangle \equiv v_s$. In this model the dark secfields $(X, \bar{X})$ respectively carry lepton number -1 and $+1$, by virtue of the renormalizable transfer operator $\mathcal{O}_T = LH_uX$. However, the lepton number is explicitly violated by the first sector, so, to guarantee the general structure of the model, we may have to turn to other symmetries, such as the generalized Z_3 symmetry of the NMSSM. We will specifically address this problem somewhere else.

We now discuss several prominent features of the model's parameter space. In the first, we will find that a moderately large λ_X, endured by perturbativity of the model up to GUT-scale, is favored to annihilate away the symmetric component. So, a properly large singlet VEV, say $v_s \sim \mathcal{O}(5)$ TeV, is necessary to make $M_X = \lambda_X v_s$ at the TeV scale. In turn, a large λA_λ may be required in the NMSSM Higgs sector. Next, the soft spectrum is rather heavy because the TeV-scale ADM is also the lightest sparticle (LSP). As a consequence, the Higgsino and singlino masses $\mu = \lambda v_s$ and $M_{\widetilde{s}} = 2\kappa v_s$ should be sufficiently heavy, which means that both λ and κ should take larger values. Finally, y_X is an important parameter controlling the chemical equilibrium decoupling temperature, and it is can not be too small otherwise $T_D < m_X$ is impossible. We will discuss it more detailedly later.

1. *A Sneutrino-like ADM*

In our model, the scalar components of the chiral superfieds X and $\bar{X}$, denoted by the same letters, transfer odd under the ordinary $R-$parity. Moreover, the dark states do not conserve a separated dark sector symmetry and thus the ADM candidate actually is also the LSP of the complete model. That is to say, ADM must be the lighter complex scalar from the $(X, \bar{X}^*)$ mixture [42]. We now explicitly check the dark sector mass spectrum. In the first, the Dirac pair approximately has a mass M_X, at the TeV scale. Secondly, $(X, \bar{X}^*)$ mix with the left-handed sneutrino $\widetilde{\nu}_L$ after electro-weak symmetry breaking. In the basis

$(\widetilde{\nu}_L, X^*, \bar{X})$, they have a mass square matrix

$$\mathcal{M}_S^2 = \begin{pmatrix} m_{\widetilde{L}}^2 & y_X A_{y_X} v_u & y_X M_X v_u \\ & M_X^2 + m_X^2 & M_X A_{\lambda_X} \\ & & M_X^2 + m_{\bar{X}}^2 \end{pmatrix}. \tag{8}$$

Since the mixings with $\widetilde{\nu}_L$ are suppressed by $y_X v_u$, then for a heavier $m_{\widetilde{L}}^2$ it is justified to first diagonalize the $(X, \bar{X}^*)$ subsystem and get two eigenstates:

$$X_1 = \cos\theta_X X + \sin\theta_X \bar{X}^*, \quad X_2 = -\sin\theta_X X + \cos\theta_X \bar{X}^*, \tag{9}$$

with θ_X the mixing angle. The corresponding mass squares are given by

$$m_{1,2}^2 = M_X^2 + \frac{m_X^2 + m_{\bar{X}}^2}{2} \mp \sqrt{(m_X^2 - m_{\bar{X}}^2)^2 + 4(M_X A_{\lambda_X})^2}. \tag{10}$$

X_1, having a lighter mass square, is the ADM (We will identify $X_1|vacuum\rangle$ and $X_1^\dagger|vacuum\rangle$ as DM and anti-DM, respectively). It is noticed that m_1^2 can be much smaller than M_X^2 in the presence of a large A_{λ_X} or negative soft mass squares.

The mixing between X_1 and $\widetilde{\nu}_L$ endows ADM with sneutrino properties and hence allows it to two-body decay alone LLE^c into a pair of leptons. In addition to that, the mixing matters in the ADM chemical equilibrium with neutrinos discussed below. We can estimate the mixing angle:

$$C_{X\widetilde{\nu}_L} \simeq \frac{y_X v_u}{m_{\widetilde{L}}^2 - m_1^2} \left(A_{y_X} \cos\theta_X - M_X \sin\theta_X\right). \tag{11}$$

For $y_X \sim \mathcal{O}(0.1)$, it is can be readily arranged to be less than $\mathcal{O}(10^{-4})$, say by lowering $\sin\theta_X$ and moreover taking a relatively small A_{y_X}. This helps to alleviate the need for exceedingly small $R-$parity violations.

2. *ADM at the earlier Universe*

At the earlier Universe, the dark sector enters thermal equilibrium with the plasma via its significant coupling to S. But such interactions conserve the dark number and thus do not transfer asymmetry from the visible sector to the dark sector. As mentioned before, transfer only proceeds after the LH_uX term becomes active. Consider the neutralino-neutrino-DM interactions

$$\mathcal{L}_{X\nu} \supset y_X U_{um} X_1 \bar{\nu} P_R \chi_m + c.c. \tag{12}$$

We have used $\widetilde{H}_u^0 = \sum_{m=1}^5 U_{um}\chi_m$ with χ_m denoting the the NMSSM five neutralinos having Majorana masses M_{χ_m}. Contributions proportional to $C_{X\widetilde{\nu}_L}$ are safely neglected. Interactions in Eq. (12) lead to the following scattering

$$X_1\nu \leftrightarrow X_1^*\bar{\nu}, \tag{13}$$

which then maintains the chemical equilibrium between the dark states and the light species. The chemical potential of DM is determined to be

$$\mu_X = -\mu_\nu. \tag{14}$$

μ_ν expresses the lepton chemical potential and is related to the quark chemical potential. It is positive, so we have a negative μ_X and then only DM survives. Recalling that ADM should be about 2.5 TeV, it is reasonable to consider $T_D \gtrsim 200$ GeV, lying above the sphaleron decoupling temperature T_{sp}. In this case, and further assume that T_D is above the critical temperature T_c, we then have

$$\frac{n_B}{n_{X_1}} = \frac{8}{5k_X} f_X^{-1}(m_1/T_D). \tag{15}$$

To get it we have decoupled the sparticles because we are considering a rather heavy SUSY spectrum. The factor k_X depends on the dark sector mass spectrum, and its value varies between 1 and 3. We will comment on it soon later.

On our purpose, the above equilibrium should break at a lower temperature T_D, when DM becomes semi-relativistic, namely $x_D \equiv T_D/m_1 \sim \mathcal{O}(0.1)$. As a rough estimation, T_D can be determined by equaling $\Gamma_{X\nu}(T_D)$, the thermal average scattering rate of Eq. (13), to the Hubble expansion rate $H(T_D) = 1.66 g_*^{1/2} T_D^2/M_{\rm Pl}$. Here g_* is the effective relativistic degrees of freedom at T_D, and in our model it is at the order 100. The rate is estimated as

$$\Gamma_{X\nu}(T_D) \simeq n_X \langle \sigma_{X\nu} v\rangle \simeq \left(0.064 g_{X_1} m_1^3 x_D^{-3/2} e^{-1/x_D}\right) \frac{|y_X U_{um}|^4}{64\pi} \frac{M_{\chi_m}^2}{(M_{\chi_m}^2 - m_1^2)^2} 2x_D, \tag{16}$$

with $g_{X_1} = 2$ the internal degrees of freedom of the complex scalar ADM. Note that one of the Feynman diagrams for the scattering cross section has neutralinos in the $s-$channel, so it shows a resonant behavior as M_{χ_m} approach to m_1.

We now show some numerical results. Combined Eq. (15) with Eq. (6), it is found that to get a TeV-scale ADM, say $m_1 = 2.4$ TeV in our model, x_D should be around 0.08, which is neither sensitive to k_X nor the ADM mass. Moreover, despite of a strong dependence on m_1, T_D does not depends on k_X much. And $T_D \simeq 200$ GeV is almost fixed, see Fig. 2. This justifies the previous assumption on T_D. In addition, to decouple the chemical equilibrium for

Eq. (13) at the proper temperature, one generically needs a sufficiently large y_X. Concretely speaking, in our model, we need

$$|y_X U_{um}|^4 \frac{M_{\chi_m}^2/m_1^2}{(M_{\chi_m}^2/m_1^2-1)^2} \sim 10^{-9}. \tag{17}$$

So, $y_X \sim 0.1$ may be needed, even if a moderately large resonant enhancement is provided.

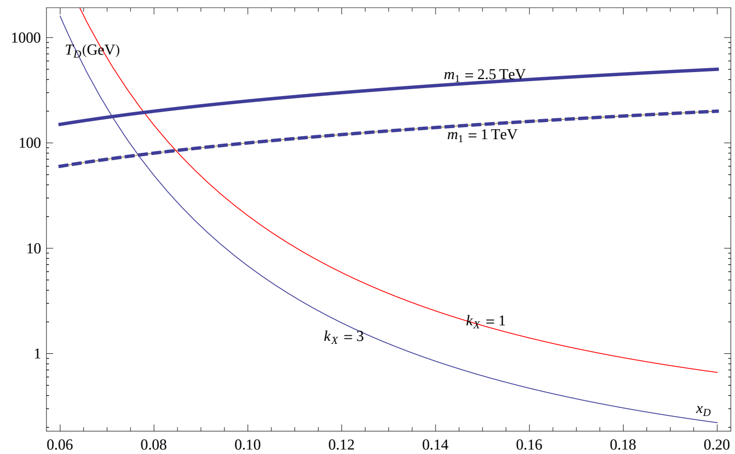

FIG. 2: A plot of heavy ADM mass solution to the cosmic coincidence puzzle in our model.

Comments are in orders. First, we have neglected other possible scattering process such as $X_1\nu \to \widetilde{t}t$, of which the scattering cross section is at order $\mathcal{O}(y_{iX}^2 y_t^2)$. However, stops are much heavier and therefore there is inadequate kinematic energy (Typically $E \sim m_X/x_D \sim$ 100 GeV) available for X and ν, as renders the scattering decouples much earlier. Next, since here the scattering is just the processes which maintains the chemical equilibrium, the neutralino mediated wash-out is not of concern. Finally, other dark sector states, the Dirac pair $(\widetilde{X}, \widetilde{\widetilde{X}})$ as well as X_2 also store appreciable DM asymmetries given that their masses are near m_1. The former can establish chemical equilibrium with neutrinos via Higgs mediated scattering. So we introduce the factor k_X, having been used previously, to account for this uncertainty:

$$k_X = \sum_{X_i} \frac{g_{X_i}}{g_{X_1}} \frac{f(m_{X_i}/T_D)}{f(m_1/T_D)}, \tag{18}$$

with X_i running over $X_{1,2}$ and the Dirac pair. Clearly, we have $1 \leqslant k_X \leqslant 3$, with the upper bound saturated when X_i are degenerate.

As the Universe cools down further, the ADM annihilates away the symmetric component by means of DM and anti-DM collisions. We need a moderately large annihilation rate $\gtrsim 10$ pb [30]. For a TeV scale DM, generically this is problematic if we require λ_X and λ sufficiently

small so as to maintain the petyrbativity of the model up to the GUT scale. Fortunately, the singlet sector is heavy (for simplicity, decoupled from the Higgs doublet sector), and thus the process $X_1X_1^* \to H_1H_2$ can be resonantly enhanced by the singlet-like CP-even Higgs bosons H_3 in the $s-$channel. Here $H_{1,2}$ are assumed to be H_u- (thus SM-) and H_d-like, respectively. In this non-mixing limit, it is readily to calculate the cross section

$$\begin{aligned}\sigma_{H_1H_2}v \simeq&\frac{\lambda_X^2}{64\pi}\left(\frac{M_X^2}{m_1^2}\right)\left(\frac{(\lambda A_\lambda)^2}{4m_1^4}\right)f(4m_1^2/m_{H_3}^2)\\ =&7.8\times\left(\frac{\lambda_X^2}{0.1}\right)\left(\frac{\lambda A_\lambda M_X}{10\,\mathrm{TeV}^2}\right)^2\left(\frac{2\,\mathrm{TeV}}{m_1}\right)^4\mathrm{pb},\end{aligned}\tag{19}$$

where the Breit-Wigner enhancement factor f can be tuned to larger values, e.g., 100 in the above estimation. Note that a large trilinear soft term A_λ, which is necessary to get a large v_s, also helps to increase the above cross section at the same time. In a word, it is not difficult to get a sufficiently large cross section to annihilate away the ADM symmetric part.

3. ADM today

We now show how does the ADM leptonic decay produce the desired asymmetric CR in our model. X_1 shares the couplings of left-handed sneutrinos $\widetilde{\nu}_{L,i}$, then, alone the $R-$parity violating operators LLE^c, it can (only) decay to a pair of charged leptons. From the data fitting in Section II, the $\mu^-\tau^+$ mode is singled out. To this end, we let $\lambda_{123}\,y_{X1}$ dominate over other similar products (This may be arranged by a flavor symmetry) and the resulted operator for ADM decay is

$$\mathcal{L}_{\rm decay}\supset C_{X\widetilde{\nu}_1}\lambda_{123}\,X_1\bar{\tau}P_L\mu.\tag{20}$$

It is crucial to note that its Hermit conjugate part is irrelevant to the ADM decay, because only DM is left today. In other words, for AMD decay, the mode with charge conjugate final states is absent. Consequently, here we get an asymmetric CR due to the different spectrum between μ and τ. In addition, the ADM life time is

$$\tau(X_1\to\tau^+\mu^-)\approx 1.7\times 10^{26}\left(\frac{10^{-4}}{C_{X\widetilde{\nu}_L}}\right)^2\left(\frac{10^{-22}}{\lambda_{123}}\right)^2\left(\frac{2\,\mathrm{TeV}}{m_1}\right)s.\tag{21}$$

When $C_{X\widetilde{\nu}_L}\sim 10^{-4}$ or even smaller, λ_{123} can be obviously larger than those in the previous works [9]. In the Appendix. A we will discuss several ways to get a very small λ_{123}.

It is worthwhile to note that in our model the sneutrino-like ADM decay does not produce other significant signatures such as neutrino flux or anti-protons (But electroweak corrections on the charged particles or τ hadronic decay can still induce a correlated anti-proton

signature [14]). The diffuse gamma ray from ICS and tau lepton decay is an exception. As the introduction stressed, it is stringently constrained by the Fermi-LAT gamma ray measurement. Here the bound is weakened because of the single τ rather than pair τ from ADM decay, rather than annihilation. Actually, it leaves an associated gamma ray signature for future observation.

Finally we briefly discuss the prospect on the direct detection of the ADM in this model. The left-handed sneutrino fraction within the ADM is negligible, which implies that the $Z-$boson mediated ADM-nucleon spin-independent scattering can not be detected. Consider the $F-$term of S: $|F_S|^2 = |\lambda_X X\bar{X} + \lambda H_u^0 H_d^0 + ...|^2$, from which we get the vertex (The Higgs sector is still in the decoupling limit)

$$-\frac{1}{\sqrt{2}}\lambda\lambda_X v \sin 2\beta \sin 2\theta_X |X_1|^2 H_1. \tag{22}$$

So, the SM-like Higgs boson $H_1 = h$ leads to a detectable spin-independent scattering cross section, which can be written as $\sigma_p = f_p^2 \mu_p^2/\pi$ [34] with $\mu_p \approx m_p$ the reduced DM-nucleon mass. Specified to this model, we have [35]

$$\begin{aligned} f_p &= -\lambda\lambda_X \sin 2\beta\ \sin 2\theta_X \frac{m_n}{2m_1}\frac{1}{m_h^2} \\ &\approx 0.8\times 10^{-9}\times\left(\frac{\lambda\lambda_X}{0.5}\right)\left(\frac{\sin 2\beta}{0.4}\right)\left(\frac{\sin 2\theta_X}{1.0}\right)\left(\frac{2\text{ TeV}}{m_1}\right)\text{GeV}^{-2}, \end{aligned} \tag{23}$$

with $m_h = 125$ GeV fixed. For σ_p from the above parameterization to maximize the scattering rate, the ADM has been excluded by the latest XENON100 data [36]. Of course, one can readily suppress this rate by turning to a much larger $\tan\beta$ and/or a smaller $\theta_X \to 0$ (Thus ADM is a pure state, either X or $\bar{X}^*$). In summary, this ADM can be directly detected, however is difficult to be excluded.

IV. CONCLUSIONS AND DISCUSSIONS

Recently, the first result of AMS-02 showed the cosmic positron fraction excess. Although confirms the previous conclusion by PAMELA, its softer spectrum feature leads to a tension with the Fermi-LAT e^+ and e^- total flux spectrum measurement. It implies that we may need a somewhat unconventional extra source to resolve this tension. In this work we propose using asymmetric cosmic ray from asymmetric dark matter late decay as a solution. We find that a multi-TeV ADM (around 3 TeV) asymmetrically decays to $\mu^-\tau^+$ can indeed significantly improve the fit using extra source from the conventional symmetric DM decay. Based on the NMSSM with $R-$parity-violating SUSY, we construct a minimal renomalizable supersymmetric model to realize that scenario. The model only introduces a pair of singlets and involves no new scales. In addition, the ADM in our model can be directly detected.

In the decaying ADM framework to explain the AMS-02 and Fermi-LAT anomalies, there are still open questions needed to be answered. First, at the tree-body decay level, it is of interest to consider modes containing quarks, say $X \to e^- u\bar{d}$. After hadronization, we will have an asymmetric proton spectrum, and $\bar{p}/(p+\bar{p}) < 0.5$. Can it lead to an acceptable anti-proton spectrum by PAMELA? Next, it is not clear whether multi decay modes with proper branching ratios can help to further improve the fits. Last, how to distinguish asymmetric CR generated by the ADM mechanism from by astrophysical mechanisms, say via measuring the e^- spectrum, is very important.

To end up this work, we would like to comment on the constraints of the non-annihilating bosonic ADM. From some astrophysical objects such as the neutron star, it is can be constrained or even excluded for light bosonic ADM [38] (But exception [39]). However, heavy bosnic ADM has not been constrained yet [37].

Acknowledgement

We thank useful discussions with Yizhong Fan. This research was supported in part by the China Postdoctoral Science Foundation (No. 2012M521136).

Appendix A: Generating small $R-$parity violation

The decaying ADM life time is extremely long, $\sim 10^{26}$s, and thus how to generate that small $R-$parity violation is challenging. In this appendix we present a simple way to explain its smallness. To that end, we introduce a pair of vector-like lepton doublets $(L_V, \bar{L}_V)$ with mass around the Planck scale. They mediate lepton number violation, which is induced by the $F-$term of some singlet $\mathcal{X}$ (namely $F_{\mathcal{X}} \neq 0$) to ordinary leptons. The model is given by

$$\frac{c_j}{M_{\rm Pl}} \int d^4\theta \bar{L}_V L_j \mathcal{X}^\dagger + \int d^2\theta \lambda_{ik} L_i L_V E_k^c + M_V L_V \bar{L}_V. \tag{A1}$$

Actually, the first term generates a tiny mixing between the vector-like leptons and the light SM leptons. The mixing is greatly suppressed by $F_{\mathcal{X}}/M_V M_{\rm Pl}$, and as a consequence the induced coefficients for the $R-$parity-violating operators $L_i L_j E_k^c$ are estimated as

$$\lambda_{ijk} \sim \lambda_{ik} c_j \frac{F_{\mathcal{X}}}{M_V M_{\rm Pl}}. \tag{A2}$$

It is interesting to note that λ_{ijk} as small as 10^{-20} can be achieved even if $F_{\mathcal{X}}/M_{\rm Pl} \sim m_{\widetilde{G}}$ with $m_{\widetilde{G}} \sim 1$ TeV the gravitino mass, the typical mass scale of soft terms in the gravity-mediated SUSY-breaking. In other words, $\mathcal{X}$ may originate in the hidden sector breaking

SUSY, and even be identified with the hidden sector SUSY-breaking spurion field.

---

[1] Planck Collaboration, P. Ade et. al., arXiv:1303.5062.

[2] O. Adriani et al. [PAMELA Collaboration], Nature 458, 607 (2009).

[3] O. Adriani, et al., Astropart. Phys. 34, 1 (2010); M. Ackermann et al. [Fermi LAT Collaboration], Phys. Rev. Lett. 108, 011103 (2012).

[4] The Fermi LAT Collaboration, A. A. Abdo et. al., Phys. Rev. Lett. 102 (2009) 181101.

[5] O. Adriani et al. [PAMELA Collaboration], Phys. Rev. Lett. 105, 121101 (2010).

[6] T. F. -: M. Ackermann *et al.* [LAT Collaboration], Astrophys. J. **761**, 91 (2012).

[7] P. Meade, M. Papucci, A. Strumia and T. Volansky, Nucl. Phys. B **831**, 178 (2010); M. Cirelli, E. Moulin, P. Panci, P. D. Serpico and A. Viana, Phys. Rev. D **86**, 083506 (2012).

[8] J. Chang, et al., Nature 456, 362 (2008); F. Aharonian, et al., Phys. Rev. Lett. 101, 261104 (2008), 0811.3894.

[9] P. -f. Yin, Q. Yuan, J. Liu, J. Zhang, X. -j. Bi and S. -h. Zhu, Phys. Rev. D **79**, 023512 (2009); A. Ibarra, D. Tran and C. Weniger, JCAP **1001**, 009 (2010); K. Ishiwata, S. Matsumoto and T. Moroi, Phys. Lett. B **675**, 446 (2009); S. -L. Chen, R. N. Mohapatra, S. Nussinov and Y. Zhang, Phys. Lett. B **677**, 311 (2009); R. C. Cotta, et al., JHEP **1101**, 064 (2011); M. Ibe, S. Iwamoto, S. Matsumoto, T. Moroi and N. Yokozaki, arXiv:1304.1483.

[10] A. Arvanitaki et al., Phys. Rev. D 79 (2009) 105022; M. Luo, L. Wang, W. Wu and G. Zhu, Phys. Lett. B **688**, 216 (2010).

[11] X. Gao, Z. Kang and T. Li, Eur. Phys. J. C 69 (2010) 467; C. D. Carone and R. Primulando, Phys. Rev. D **84**, 035002 (2011); Y. Kajiyama, H. Okada and T. Toma, arXiv:1304.2680.

[12] M. Aguilar, et al., Physical Review Letters 110, 141102 (2013).

[13] L. Feng, R. -Z. Yang, H. -N. He, T. -K. Dong, Y. -Z. Fan and J. Chang, arXiv:1303.0530.

[14] A. De Simone, A. Riotto and W. Xue, arXiv:1304.1336 [hep-ph].

[15] Q. Yuan, X.-J. Bi, G.-M. Chen, Y.-Q. Guo, S.-J. Lin, et al. (2013), 1304.1482.

[16] H. -B. Jin, Y. -L. Wu and Y. -F. Zhou, arXiv:1304.1997 [hep-ph].

[17] T. Linden and S. Profumo, arXiv:1304.1791; P. -F. Yin, Z. -H. Yu, Q. Yuan and X. -J. Bi, arXiv:1304.4128 [astro-ph.HE].

[18] I. Cholis and D. Hooper, arXiv:1304.1840;

[19] Q. Yuan and X. -J. Bi, arXiv:1304.2687 [astro-ph.HE].

[20] M. T. Frandsen, I. Masina and F. Sannino, Phys. Rev. D **83**, 127301 (2011); I. Masina and F. Sannino, JCAP 1109 (2011) 021.

[21] S. Chang and L. Goodenough, Phys. Rev. D **84**, 023524 (2011) [arXiv:1105.3976 [hep-ph]].

[22] A. W. Strong, and I. V. Moskalenko, Astrophys. J. **509** 212 (1998).

[23] J. F. Navarro *et al.*, Mon. Not. Roy. Astron. Soc. **402** (2010) 21

[24] I. Masina and F. Sannino, arXiv:1304.2800 [hep-ph].

[25] Z. Kang and T. Li, JHEP **1210**, 150 (2012).

[26] See a review: H. Davoudiasl and R. N. Mohapatra, New J. Phys. **14**, 095011 (2012).

[27] J.A. Harvey and M.S. Turner, Phys. Rev. D 42 (1990) 3344.

[28] E. W. Kolb and M. S. Turner, The Early Universe, Addison-Wesley (1990).

[29] M. R. Buckley and L. Randall, JHEP **1109**, 009 (2011).

[30] M. L. Graesser, I. M. Shoemaker and L. Vecchi, JHEP **1110**, 110 (2011).

[31] P.-H. Gu, M. Lindner, U. Sarkar and X. Zhang, Phys. Rev. D 83 (2011) 055008; Y. Cui, L. Randall and B. Shuve, JHEP **1204**, 075 (2012); S. Davidson and M. Elmer, JHEP **1210**, 148 (2012); H. Kuismanen and I. Vilja, Phys. Rev. D **87**, 015005 (2013).

[32] D. E. Kaplan, M. A. Luty and K. M. Zurek, Phys. Rev. D 79, 115016 (2009)

[33] Z. Kang, J. Li, T. Li, T. Liu and J. Yang, arXiv:1102.5644 [hep-ph].

[34] G. Jungman, M. Kamionkowski and K. Griest, Phys. Rept. 267, 195 (1996).

[35] X. Gao, Z. Kang and T. Li, JCAP **1301**, 021 (2013).

[36] E. Aprile *et al.* [XENON100 Collaboration], Phys. Rev. Lett. **109**, 181301 (2012).

[37] C. Kouvaris and P. Tinyakov, arXiv:1212.4075 [astro-ph.HE].

[38] S. D. McDermott, H.-B. Yu and K.M. Zurek, Phys. Rev. D 85 (2012) 023519; C. Kouvaris and P. Tinyakov, Phys. Rev. Lett. 107 (2011) 091301; I. Lopes and J. Silk, Astrophys. J. **757**, 130 (2012);

[39] N. F. Bell, A. Melatos and K. Petraki, arXiv:1301.6811.

[40] ATIC and HESS [8], etc., also reported total flux excess, but for simplicity we only mention Fermi-LAT hereafter.

[41] See a similar point in the recent work [24] appearing on the arXiv during the preparation of this work. While Ref. [16] also considered the charge asymmetric CR scenario and draw a negative conclusion. Basically, that may be due to the fact that authors of Ref. [16] actually take a constant instead of energy-dependent asymmetry.

[42] Within the MSSM, the left-handed sneutrino in principle can be a leptonic decaying ADM proposed in the text. This is achieved by suppressing the neutralino mediated charge wash-out effect via a very heavy neutralino spectrum, say the bino has a mass around 100 TeV. We leave such an interesting scenario for future study.